

**PCAS 21 (2018/2019)**  
**Supervised Project Report**  
**(ANTA604)**

---

**Quantifying Sea Ice Trends in the Southern Ocean: is  
*Extent* or *Area* the Better Measure?**

Bryony Freer

Student ID: 66666458

**Supervisor:** Dr Wolfgang Rack

---

Word count: 8910

This report presents an assessment of the relationship between sea ice area and extent measurements in the Southern Ocean, in order to scrutinise the significance of the reported trend of increasing Antarctic sea ice over the past 40 years. Two key research questions are addressed: How are Antarctic sea ice *extent* and *area* values calculated and what information (and to what accuracy) are they actually telling us about sea ice mass balance? How do measurements of sea ice extent and area compare between that derived from low resolution and high-resolution data? The methods undertaken include a close examination of the NSIDC sea ice concentration, area and extent data trends from 1978-2016, and a case study analysis in the Weddell Sea that compares sea ice concentration, extent and area data derived from low resolution passive microwave radiometers (SSM/IS and AMS2) and higher resolution SAR. The findings reveal that the average trend conceals a large amount of spatial and seasonal variability and that there are several extreme months throughout the record where extent anomalies significantly exceed area anomalies. It is suggested that this could be a reflection of either physical processes (e.g. wind behaviour) that may vary between regions, or instrumental errors. However, the fact that measures of sea ice thickness are not incorporated into record of sea ice cover, points to the conclusion that the reported rising trend in Antarctic sea ice cover in the past few decades is highly incomplete and cannot be used to interpret sea ice mass balance changes.

# Contents

1. Introduction.....	3
1.1. Background on Sea Ice.....	3
1.2. Global Monitoring of Sea Ice.....	3
1.2.1. Historical Record.....	3
1.2.2. Passive Microwave Sensors.....	4
1.2.3. Passive Microwave-Derived Sea Ice Products.....	4
1.2.4. Passive Microwave Data for Sea Ice Monitoring: Pros and Cons.....	5
1.2.5. Other Satellite-Borne Sensor Types.....	6
1.3. Sea Ice Concentration, Extent and Area.....	6
1.4. Report Structure.....	7
2. Methodology.....	7
2.1. Analysis of NSIDC Sea Ice Extent and Area Trends.....	7
2.2. Dataset Comparison: A Weddell Sea Case Study.....	8
2.3. Methodological Limitations.....	11
3. Results.....	11
3.1. NSIDC Sea Ice Extent and Area Trends.....	11
3.1.1. Total Antarctica 1978-2016.....	11
3.1.2. Regional Trends 1978-2016.....	13
3.1.3. Seasonal Trends 1978-2016.....	13
3.1.4. 2014/5 Extreme Positive Anomaly.....	14
3.1.5. 2016 Extreme Negative Anomaly.....	14
3.2. Case Comparison Study: Weddell Sea.....	15
3.2.1. Study Site 1:.....	15
3.2.2. Study Site 2:.....	17
4. Discussion.....	19
4.1. NSIDC Antarctic Sea Ice Trends.....	19
4.1.1. Relevance for Antarctic Sea Ice Mass Balance.....	19
4.1.2. Relationship between Extent and Area Trends.....	19
4.1.3. Potential Causes of Area and Extent Discrepancies in Extreme Months.....	20
4.1.4. Implications of Findings.....	22
4.2. Case Comparison Study: Weddell Sea.....	22
4.2.1. Difference in Measurements between Sensors.....	22
4.2.2. Potential Causes of Discrepancies between Sensors.....	23
4.2.3. Implications of Case Study Findings.....	25
5. Conclusions.....	25
6. Reference List.....	27

## 1. Introduction

Since routine measurements began in 1978, Antarctica has experienced a modest increase in sea ice extent and concentration (Macalady and Thomas, 2017). In the context of a globally warming climate, this trend is often seen as a surprising paradox that presents a conundrum for global climate change science (Massonet et al., 2015; Turner et al., 2015).

This study aims to examine the significance of this trend, by assessing very closely the ways in which sea ice information is measured, processed and reported. The report begins with background on Antarctic sea ice analysis, explaining how we come to obtain values of sea ice extent and area; the two parameters that are the focus of the research.

### 1.1. Background on Sea Ice

Sea ice plays an important role in the global climate system and acts as a bellwether of change, both affecting and reflecting changes in other components of the system. The formation and melt of sea ice are vital factors in the exchange of heat, gases and energy between the atmosphere and ocean, not only acting as a physical barrier and powerful insulator (Maykut, 1986), but also causing changes in albedo influencing the Earth's radiation budget (Woodhouse, 2006) and playing a major role in stabilising the ocean column and circulation patterns (Timmermann et al., 2001). It is therefore extremely important that we obtain regular information on the sea ice coverage and ice type to input into models (Woodhouse, 2006). Errors in sea ice concentration values of even a few percent can make a significant difference in calculations of heat and salinity flux and ice production rate in models (Parkinson et al., 2001). For this reason it is critical that we understand how this data has been, and is, obtained (and the associated uncertainties) when interpreting trends through time.

### 1.2. Global Monitoring of Sea Ice

#### 1.2.1. Historical Record

We have very little information about the variability of Antarctic sea ice pre-satellite era. However, since passive microwave radiometers were first launched on satellites in the late 1970s, we have a routine, robust and geographically extensive record of sea ice variability in both hemispheres (Macalady & Thomas, 2017). As a result, polar sea ice distribution is now one of the best recorded of all climate variables on earth (Parkinson & Cavalieri, 2012). These instruments directly measure surface emissivity, which algorithms convert into measurements of sea ice concentration. In recent years, other techniques have started to be employed to monitor sea ice changes, including multi-polarisation and fully polarimetric Synthetic Aperture Radars (SARs – e.g. Sentinel-1), hyperspectral imagers, laser and radar altimeters (e.g. onboard CryoSAT), as well as the widely-used medium to high resolution optical sensors like MODIS and Landsat (Lubin & Massom, 2006). However it is still the measure of sea ice extent derived from passive microwave sensors that the National Snow and Ice Data Centre (NSIDC) use to report sea ice trends.

### 1.2.2. Passive Microwave Sensors

A number of passive microwave sensors onboard different satellites have been used since the 1970s to develop sea ice concentration, area and extent products (Liu et al., 2016).

**SMMR:** This began with the launch of the Scanning Multichannel Microwave Radiometer (SMMR) on NASA's Nimbus 7 satellite in late October 1978, which collected data *every other* day until 20<sup>th</sup> August 1987. The SMMR (as with SSM/I(S) that followed) was a dual polarised and multi-frequency microwave radiometer that measures surface brightness temperatures.

#### **BOX 1: SSM/I Instrument Fact File**

- **Orbit:** sun-synchronous, near-polar
- **Altitude:** 883km
- **Swath width:** 1394km
- **Polarisation:** measures H and V polarised radiances at 19.4, 37.0 and 85.5GHz, and only V polarised at 22.2GHz
- **Effective FOV:** ranges from 69x43km at 19GHz to 15x13km at 85.5GHz
- **Grid size:** 25x25km

**SSM/I:** It was followed by the Special Sensor Microwave/Imager (SSM/I), launched on the US Department of Defense's Defense Meteorological Satellite Program (DMSP) in June 1987 (satellites F8, F11 and F13), which collected data *every day* for most of the period 9 July 1987 until late 2007. Detailed specifications of the spacecraft and instrument are presented in Colton and Poe (1999) and Raytheon (2000) and a summary fact file in box 1.

**SMM/IS:** Following the deterioration of the F13 SSM/I, another instrument, the Special Sensor Microwave Imager Sounder (SSM/IS), was launched on the DMSP F17 satellite in November 2006 to continue the daily record (Parkinson & Cavalieri, 2012).

**AMSR2:** Since 4 July 2012 the SSM/I(S) dataset has been complemented by that of the higher resolution Advanced Microwave Scanning Radiometer 2 (AMSR2) instrument, which launched onboard the Japanese satellite Global Change Observation Mission 1<sup>st</sup>-Water (GCOM-W1) on 1 May.

### 1.2.3. Passive Microwave-Derived Sea Ice Products

Brightness temperatures recorded by passive microwave sensors are used to generate sea ice concentration products through a number of algorithms. The most common sea ice products, and the ones used in this study, are described here.

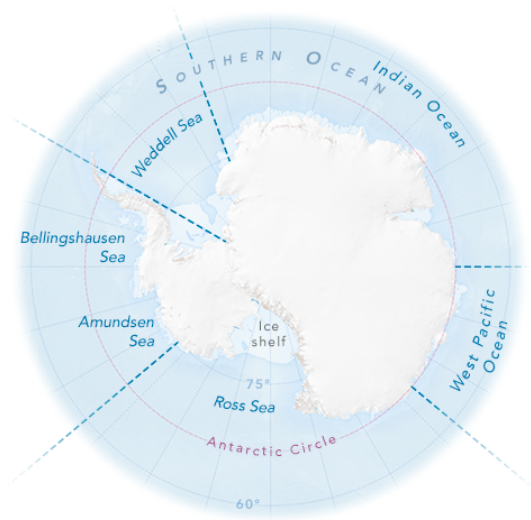
**NSIDC Sea Ice Index (Time-Series):** The NSIDC Sea Ice Index provides the longest-running record of global sea ice cover from 1978 to 2016 and is the most common product for monitoring changes in sea ice cover (Liu et al., 2016). It combines the data recorded by the SMMR (November 1978 to July 1987), SSM/I (August 1987 to December 2007) and SMM/IS (January 2008 to December 2016), which, using the NASA Team (NT) algorithm (described in Cavalieri, 1994), is converted into datasets of daily and monthly sea ice concentration, extent and area time-series for both hemispheres. In the southern hemisphere, datasets are available for the Total Antarctic as well as the five Southern Ocean sectors, as shown in figure 1. These have been processed by the Goddard Space Flight Centre (GSFC) to ensure continuity in the dataset. A Near-Real-Time product is also distributed by the NSIDC which continues this dataset from December 2016 until the present

day, but this has not been as tightly quality controlled, and so is excluded from the main sea ice record until it has undertaken the additional GSFC processing (Fetterer et al., 2016).

**NSIDC Sea Ice Index (GeoTiffs):** Daily and monthly GeoTIFF files are available from the NSIDC index for both concentration and extent data that can be downloaded and used immediately in a GIS software (Fetterer et al., 2016).

**AMSR2 Sea Ice Concentration (GeoTiffs):** A daily sea ice concentration product is generated using the enhanced NASA Team (NT2) algorithm described by Markus & Cavalieri (2000, 2009) and mapped to the same polar stereographic projection as the SMMR-SSM/I(S) data to ensure consistency between products (Meier et al., 2017). The data products are available (July 2012 to present) from the Japanese Aerospace Exploration Agency (JAXA) but have yet to be incorporated in the NSIDC Sea Ice Index.

**AMSR2 Sea Ice Concentration (GeoTiffs):** Daily sea ice concentration maps at 6.25km resolution are available as GeoTiffs for the last 30 days from the PolarView interface, operated by the University of Bremen.



**Figure 1** - The five Southern Ocean sectors: Weddell Sea 60°W to 20°E (plus the small area of ocean east of the Peninsula and 60°W); Indian Ocean 20°E to 90°E; Pacific Ocean 90°E to 160°E; Ross Sea 160°E to 130°W; combined Bellingshausen-Amundsen Seas 130°W to 60°W. (Cavalieri & Parkinson, 2008). Image Source: NASA (2016)

#### 1.2.4. Passive Microwave Data for Sea Ice Monitoring: Pros and Cons

One of the main advantages of passive microwave sensors for monitoring sea ice is their all-weather capability, and especially the ability to penetrate polar darkness. There is also a high temporal resolution with measurements obtained daily, which is critical for monitoring such a dynamic environment as the sea ice zone (Woodhouse, 2006). However, these do come at the expense of spatial resolution, which is relatively coarse (25km for SMMR and SMM/I; 6.25km for AMSR2). This is due to the relative size of microwaves being large compared to the size of the antenna (Woodhouse, 2006). Along with the mixed-pixel problem and coastal contamination effects, this is likely to compromise the instruments' accuracy (Lubin & Massom, 2006), which should be taken into consideration when interpreting the data. Furthermore, the low resolution data may be adequate for use in large-scale climate studies, but are much less useful for navigation and more detailed studies of ice dynamics and meteorology (Liu et al., 2016).

### 1.2.5. Other Satellite-Borne Sensor Types

**Active Microwave:** In an attempt to resolve the resolution shortcomings of the passive microwave datasets, active microwave sensors, such as space-borne synthetic aperture radar (SAR), have increasingly been contributing to the remote sensing of sea ice. The higher resolution (e.g. 80m for Sentinel-1) minimises the mixed pixel problem (Dierking, 2013) and enables users to resolve individual morphological features, such as leads, polynyas and pressure ridges (Melling, 1998). Ice concentration algorithms for SAR have been developed, although no operational products currently exist (Karvonen, 2014).

**Visible and Infrared (VIR):** VIR data offer a high resolution alternative. For example, methods have been developed to estimate ice concentration from VIR imagers such as the Advanced Very High Resolution Radiometer (AVHRR), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Visible Infrared Imaging Radiometer Suite (VIIRS) (e.g. Massom & Comiso, 1994; Drue & Heinemann, 2004; Baker, 2011) but they are largely limited by the fact that they only function in clear-sky conditions and the polar summer (Liu et al., 2016).

**Satellite Altimeters:** The radar altimeter SIRAL on Cryosat-2 and the laser altimeter aboard the ICESat missions have been utilised for monitoring sea ice thickness (using measurements of freeboard), but these have not yet been integrated with the historical trends of sea ice area and extent (Kwok, 2010).

## 1.3. Sea Ice Concentration, Extent and Area

**Sea ice concentration** describes the percentage of a given area of ocean that is covered in sea ice. As described in section 1.2, this is calculated from measured of surface emissivity derived from passive microwave sensors. Concentration data is then processed to provide measures of sea ice extent and area, which are defined here:

**Sea ice extent** is the total area of all grid cells that have a sea ice concentration of 15% or above (Parkinson et al., 1999). Grid cells are either defined as “sea ice-covered” or “not sea ice-covered” depending on whether the measured concentrations are above or below this 15% threshold. The boundary between these two classifications is known as the *ice edge*. Extent is the measure traditionally used by the NSIDC to report Antarctic sea ice variability.

**Sea ice area** is the total area of ice coverage only, calculated as the sum of pixel area multiplied by the concentration in that pixel (Parkinson, 1999). In the NSIDC record, this is only calculated for pixels with sea ice concentrations greater than 15%.

Although seemingly similar, these two measures do tell us different things about total sea ice coverage, and this research is interested in understanding whether this difference is significant in the reported trend through time.



## 1.4. Report Structure

Therefore, this report will investigate whether extent or area is the better measure for quantifying sea ice trends in Antarctica. Two key research questions will provide the focus for the report:

1. How are Antarctic sea ice *extent* and *area* values calculated and what information (and to what accuracy) are they actually telling us about sea ice mass balance? Is there any difference when we look at trends in area compared to extent?
2. How do measurements of sea ice extent and area compare between that derived from low resolution and high resolution data?

This report aims to address these questions firstly by examining the NSIDC sea ice concentration, area and extent data trends from 1978-2016, and then by undertaking a case study analysis in the Weddell Sea to compare sea ice concentration, extent and area data derived from passive microwave sensors (used to generate trends) and higher resolution, more accurate, datasets.

## 2. Methodology

### 2.1. Analysis of NSIDC Sea Ice Extent and Area Trends

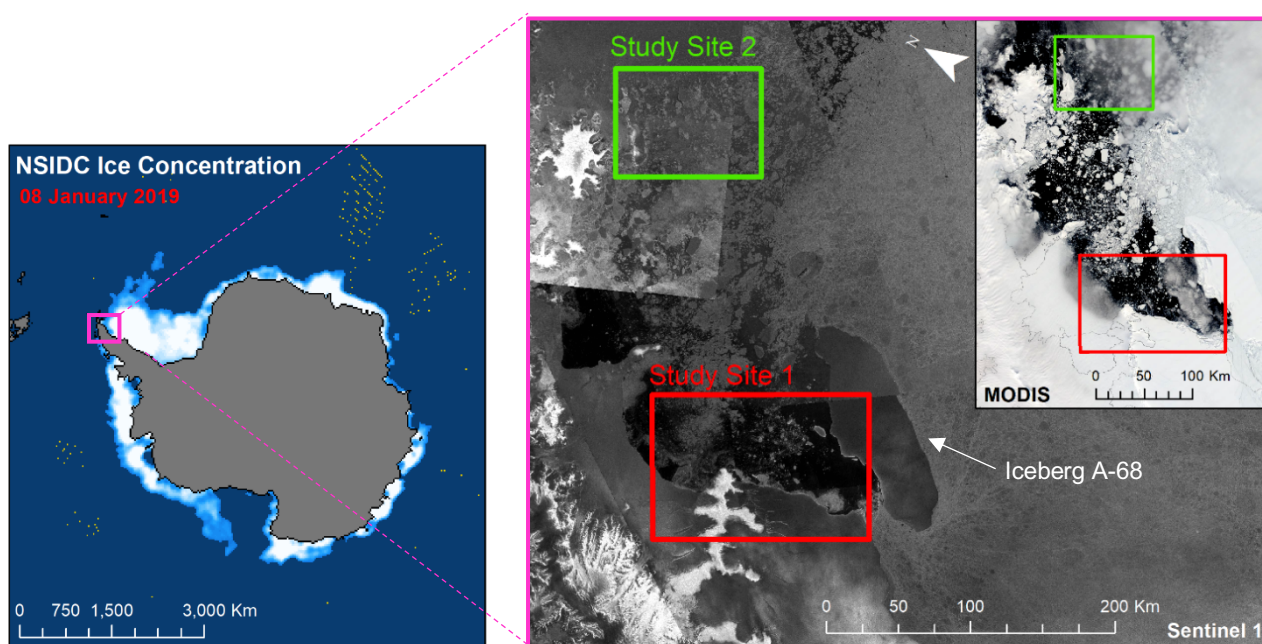
Monthly sea ice extent and area data from November 1978 to December 2016 were downloaded from the NSIDC Sea Ice Index (as described in section ...) and analysed in Microsoft Excel. It was decided to focus analysis predominantly on the monthly anomaly dataset (deviation from the 1981-2010 mean), as this shows change through time more clearly by removing the influence of the annual sea ice growth and decay cycle and hence show change through time more clearly. The sea ice *extent* and *area* anomaly trends were directly compared to one another in order to assess their relationship; in particular identifying any periods where there were significant discrepancies between extent and area trends. This was undertaken both for the total Antarctic trends and those for the five individual Southern Ocean sectors to look for any regional patterns. Trends by austral season were also analysed.

Finally, the period of 2014 to 2016 was analysed in closer detail, to investigate the extent and area trends over the two extreme sea ice extents reported during this time: the record high extent in September 2014, followed by a transition to an extreme low at the end of 2016. Where discrepancies in area and extent values were found, a closer analysis of the regional patterns was undertaken to identify any possible regional drivers.

## 2.2. Dataset Comparison: A Weddell Sea Case Study

For the second part of this research, a case comparison study was undertaken in the Weddell Sea to compare how measurements of sea ice concentration, extent and area differ (if at all) between the low resolution passive microwave data and high resolution SAR. The aim was to assess the accuracy of the passive microwave datasets used to produce the NSIDC Sea Ice Index, and to identify if any discrepancies on this small scale could be influencing the discrepancies seen in the NSIDC extent and area trends analysed above.

The Weddell Sea was chosen as a location due the availability of real-time data and imagery from the *2019 Weddell Sea Expedition* as well as the persistence of sea ice throughout the summer months (unlike in most other parts of the Antarctic coastline). The date of 8 January 2019 was selected due to the availability of overlapping SAR (Sentinel-1), AMSR2 and SSM/IS data and cloud-free MODIS imagery (used to assist the interpretation of the SAR). Within the wider area, two study sites were selected that encompassed a range of surface environments; location shown in figure 2 . Study site 1 contains 24 SSM/IS pixels and was chosen as it lies on the boundary of the NSIDC land/coast mask, contains some ice shelves and the large iceberg A-68 (terrestrial-borne ice) as well as ocean areas with a range of sea ice concentrations. Study site 2 contains 12 SSM/IS pixels and is situated completely in the marginal ice zone and straddles the ice edge (as defined by the SSM/IS extent dataset).

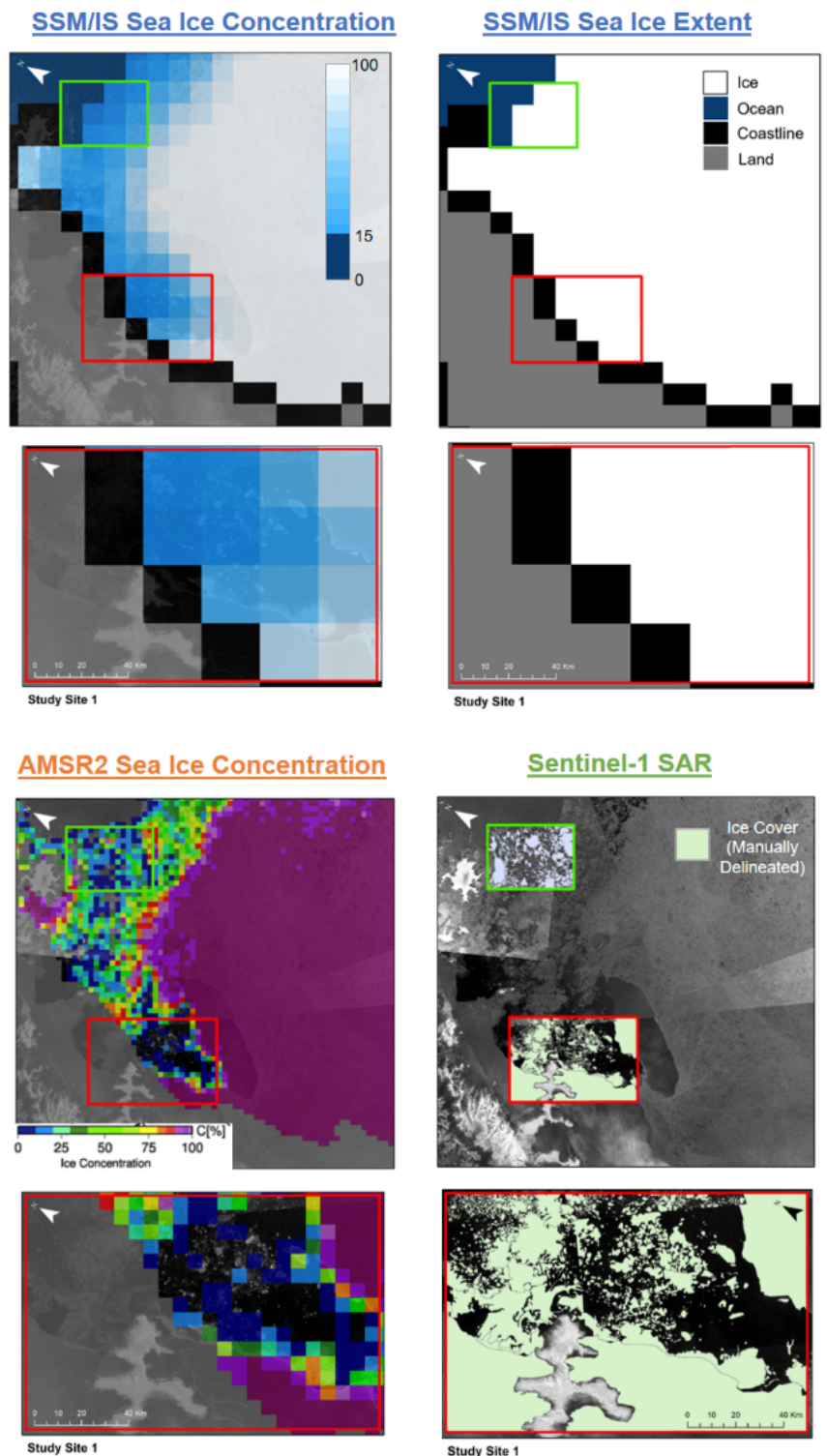


**Figure 2** - Location of the Weddell Sea case study on a map of Antarctic sea ice concentration for 8 January 2019. The specific locations of study sites 1 and 2 within this are shown on Sentinel-1 SAR imagery (inset on MODIS imagery). Land areas appear bright white, ice appears grey (sea ice tends to appear lighter than ice shelves and icebergs e.g. iceberg A-68) and open ocean appears black.



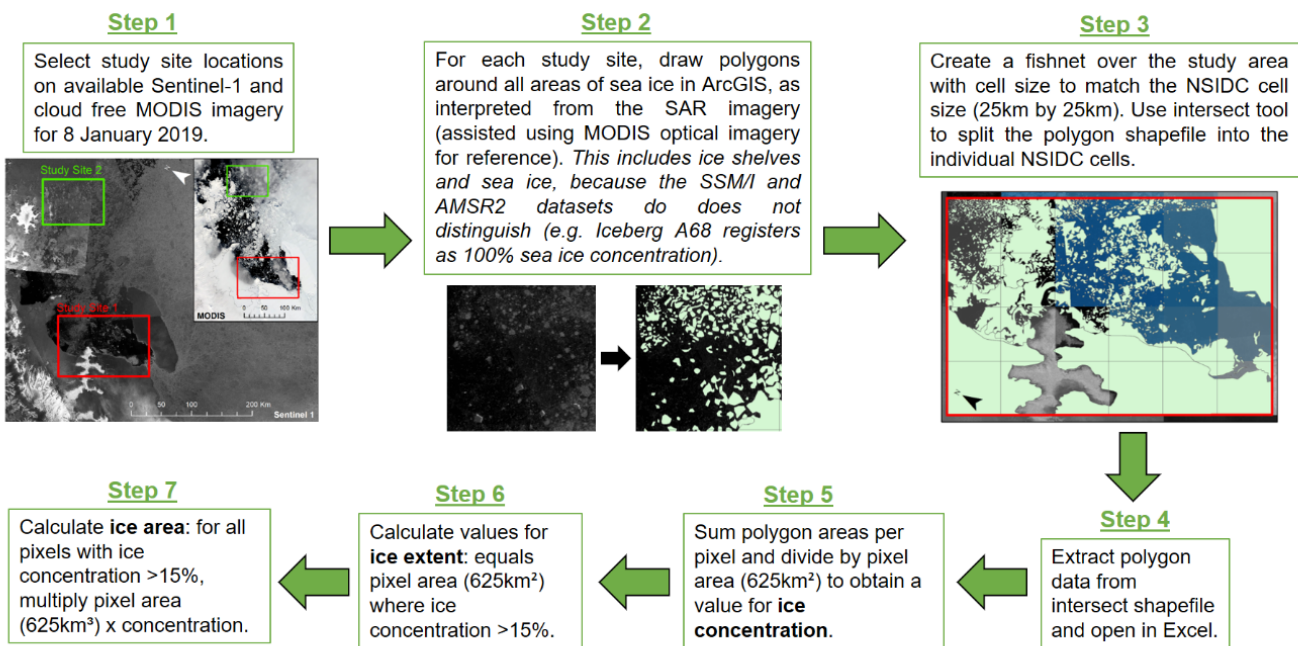
The four datasets assessed in this comparison are shown in figure 3 and the inset maps of study site 1 show the varying pixel resolution between the sensors. The SSM/IS pixel size of 25kmx25km was used to create a grid of pixels in each study site for the comparison study, and the methods undertaken are described in figure 4 . In both study sites, a manual interpretation of sea ice coverage from high resolution (80m) Sentinel-1 SAR imagery was carried out in ArcMap 10.6 by drawing polygons around all areas of sea ice. MODIS imagery was used in conjunction with the SAR data to assist with the interpretations. From these results, values of sea ice concentration, extent and area in each 25x25km grid cell were calculated (as described in figure 4).

Corresponding values were then extracted from the SSM/IS concentration and extent and AMSR2 concentration datasets over the same 25x25km grid cells, according to the methods described in figure 5 .



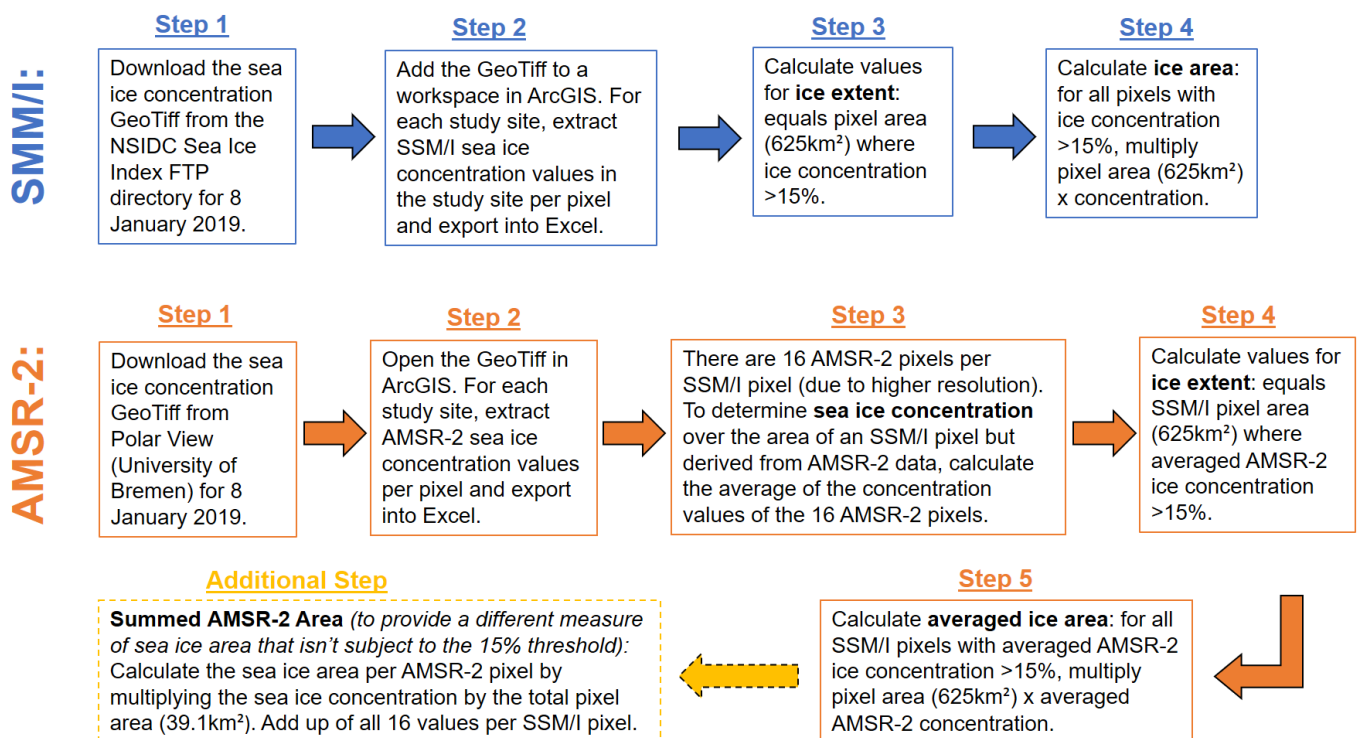
**Figure 3** - Datasets used in the Weddell Sea case study, with zoom in of study site 1. SSM/IS imagery have a spatial resolution of 25x25km; AMSR2 resolution is 6.25x6.25km; SAR is 80x80m.

## Manual Interpretation of Sea Ice Concentration from SAR Imagery:



**Figure 4** - Flowchart of methods undertaken in the manual interpretation of sea ice concentrations from SAR imagery (with MODIS as reference) for the two Weddell Sea study sites.

## Deriving Sea Ice Concentration, Area and Extent from Passive Microwave Imagery:



**Figure 5** - Flowchart of methods undertaken to derive values of sea ice concentration, extent and area from passive microwave datasets (SSM/I and AMSR-2) for the two Weddell Sea study sites.

## 2.3. Methodological Limitations

It is important to consider the methodological limitations of this study when interpreting the results. Due to time constraints there were challenges obtaining appropriate data, particularly for the Weddell Sea case study. There is also likely to be discrepancies in the time of day that the datasets were collected, relating to the differing satellite overpass times. This is likely to compromise the comparisons here since the marginal ice zone summer is such a dynamic environment in which relatively rapid changes can occur within hours (Steffen & Schweiger, 1991). It is therefore possible that a pixel could be measured as having a high sea ice concentration at 6am when one sensor passes over, and by 6pm winds could have forced this ice away leaving open ocean and a measurement of low concentration measurement by the next sensor.

Furthermore, the SAR imagery comprises a composite of multiple image mosaics taken over the period 4-8<sup>th</sup> January. This manifests in visible inconsistencies at the points at which the images join and could mean that in some areas the ice coverage identified was in fact that from a few days earlier. Human error during the manual interpretation of the ice cover in ArcMap could also be introducing a degree of uncertainty into the results.

In addition, there are known instrumental errors within the passive microwave datasets that are likely to introduce uncertainty into the results, both of the historical NSIDC trends and the Weddell Sea case study, however these will be discussed separately in section 4.2 of this report.

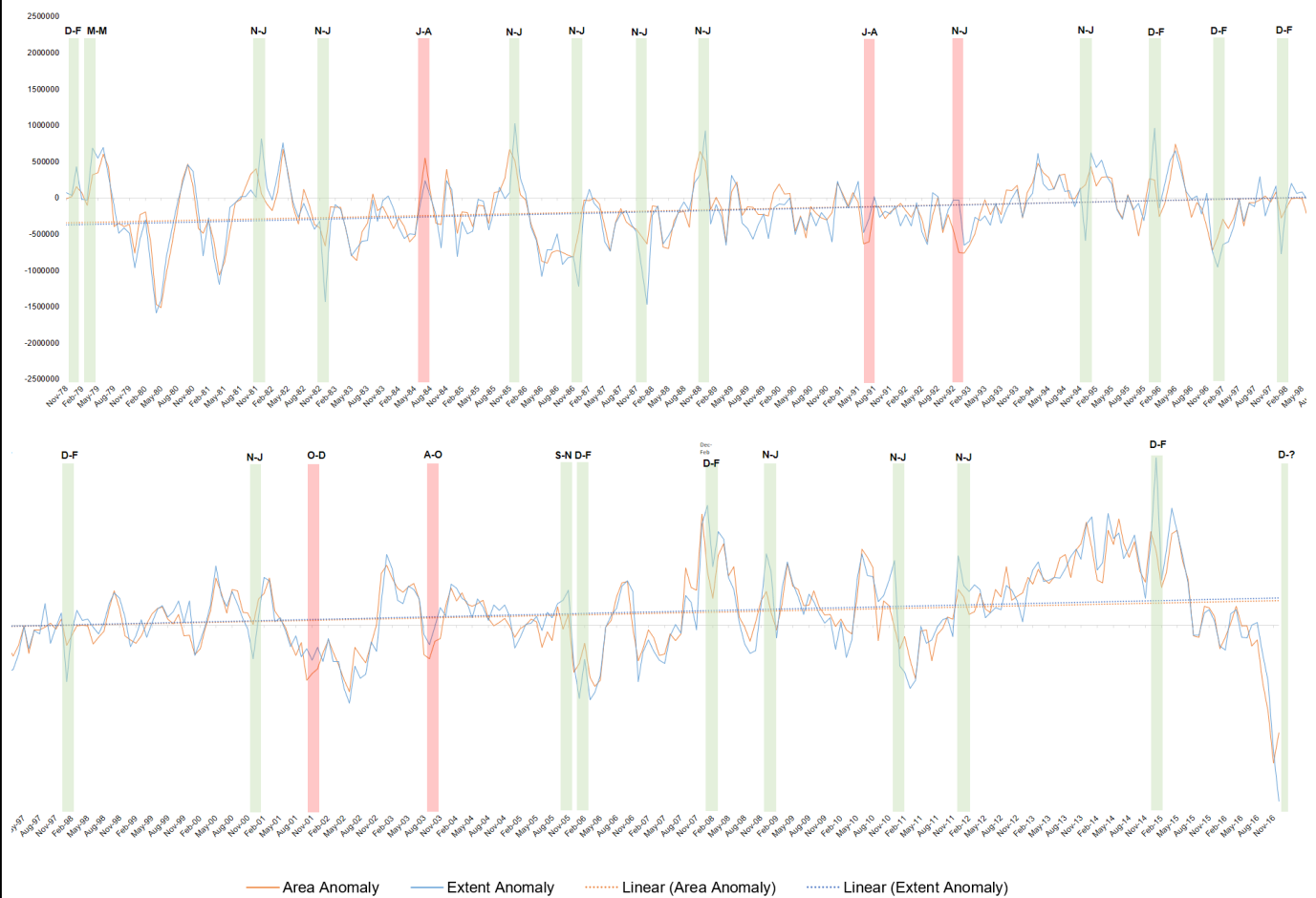
## 3. Results

### 3.1. NSIDC Sea Ice Extent and Area Trends

#### 3.1.1. Total Antarctica 1978-2016

Figure 6 shows the NSIDC monthly anomaly data for Antarctic sea ice *extent* (in blue) and *area* (in orange), as measured by SSMR and SSM/I(S) from November 1978 to December 2016. Extent and area trends appear to largely fit well together, with both linear trend lines showing an overall increase over the time series. *Extent* has a slightly greater rate of change (+19510km<sup>2</sup> per year) compared to *area* (+17798km<sup>2</sup> per year). However, where there are significant discrepancies between the measures is in the months of extreme anomalies (most deviation from the mean). These areas have been highlighted in figure6; green shading indicates extreme months where extent anomaly values are of considerably greater magnitude than area, and red shading where area anomalies are of considerably greater magnitude than extent. Of the 21 green-shaded peaks where extent anomaly > area anomaly, 19 occur between November and February (austral summer). The greatest of these occurs with the extreme positive anomaly in Dec-Feb 2014/15, shortly followed by an extreme negative anomaly in Dec 2016. The data from this period will be analysed more closely in sections 3.1.4-5. The three red-shaded peaks where area anomaly > extent anomaly occurred in different seasons and the discrepancies are of lesser magnitude than those where extent > area. It ought to be noted that not all extreme months have such a discrepancy between the extent and area anomalies, and those peaks with close correlation tend to occur in austral autumn and winter months.

## Total Antarctic monthly Extent and Area Anomalies 1978-2016

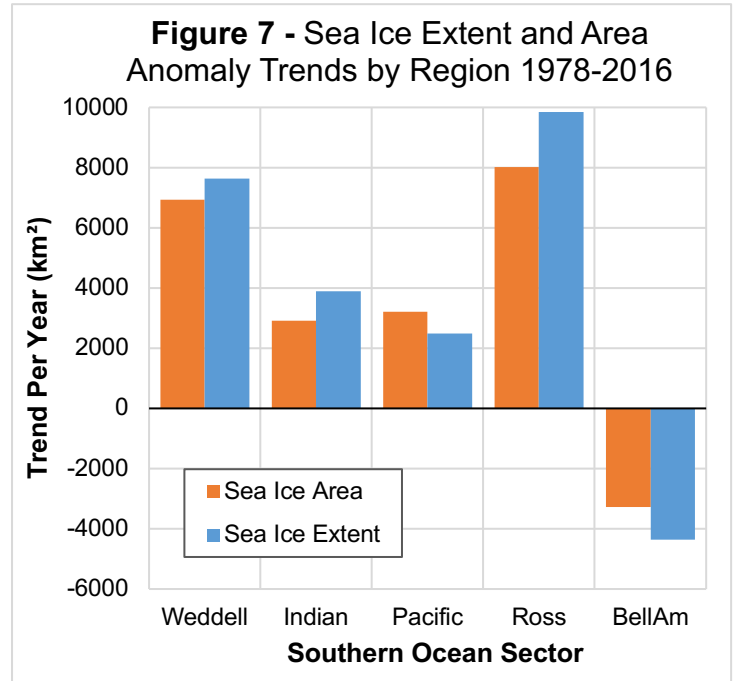


**Figure 6** - Monthly Antarctic sea ice area and extent anomalies data for total Antarctica 1978-2016 (NSIDC, 2019). Extreme months where there is a significant discrepancy between values of area and extent anomalies are shaded (in green where extent anomaly > area anomaly; in red where area anomaly > extent anomaly). The months in which these occur are labelled (e.g. D-F = December-February).



### 3.1.2. Regional Trends 1978-2016

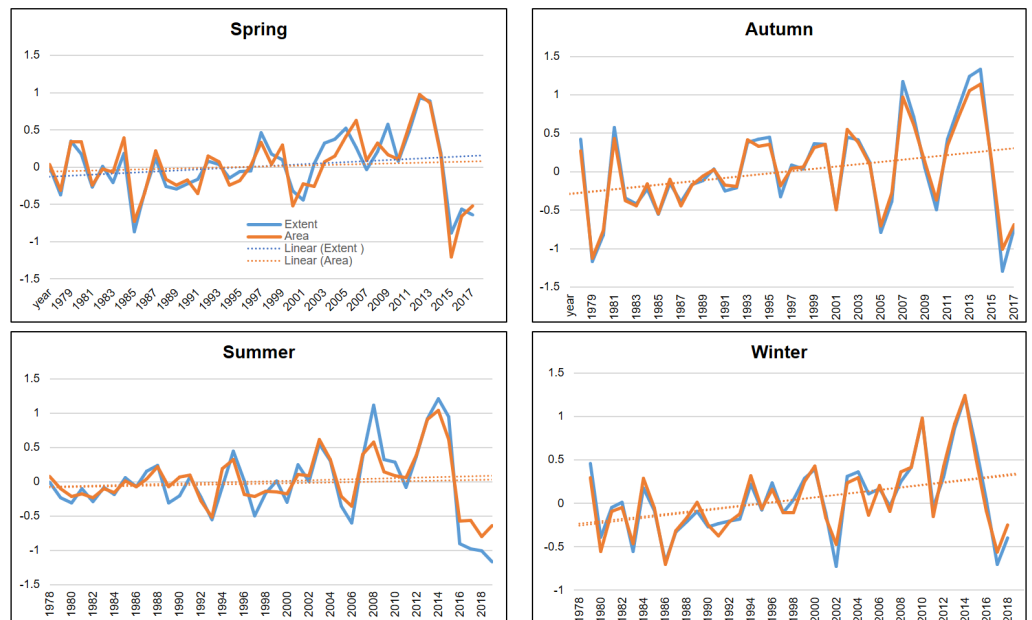
Figure 7 displays the annual trends in sea ice area and extent for each of the five Southern Ocean sectors during the same period 1978-2016, and it is clear that there is significant regional variability. Both measures show that the greatest annual increase has been observed in the Ross Sea sector, closely followed by the Weddell Sea, and that there has been a considerable annual decrease in the Bellingshausen-Amundsen sector. There are differences in the magnitude of trends between measures though, with extent having a trend of greater magnitude than area in all sectors apart from the Pacific. The largest discrepancy is in the Ross Sea sector, with extent increasing by 9840km<sup>2</sup> (3sf) per year, compared to 8020km<sup>2</sup> (3sf) per year for area.



### 3.1.3. Seasonal Trends 1978-2016

**Figure 8 - Antarctic Sea Ice Extent and Area Anomalies by Season, 1978-2016**

Figure 8 shows the sea ice area and extent trends 1978-2016 by austral season. In general terms, anomaly magnitudes can be seen to get greater through time. For austral autumn and winter, the extent and area anomalies match very closely and both show a rising trend through time. Spring and summer have linear trends through time of much smaller magnitude. In spring there are more discrepancies between measures (notably since 2000) but the greatest discrepancies occur in summer (largely since 1990), with extent anomalies often of a greater magnitude than area.



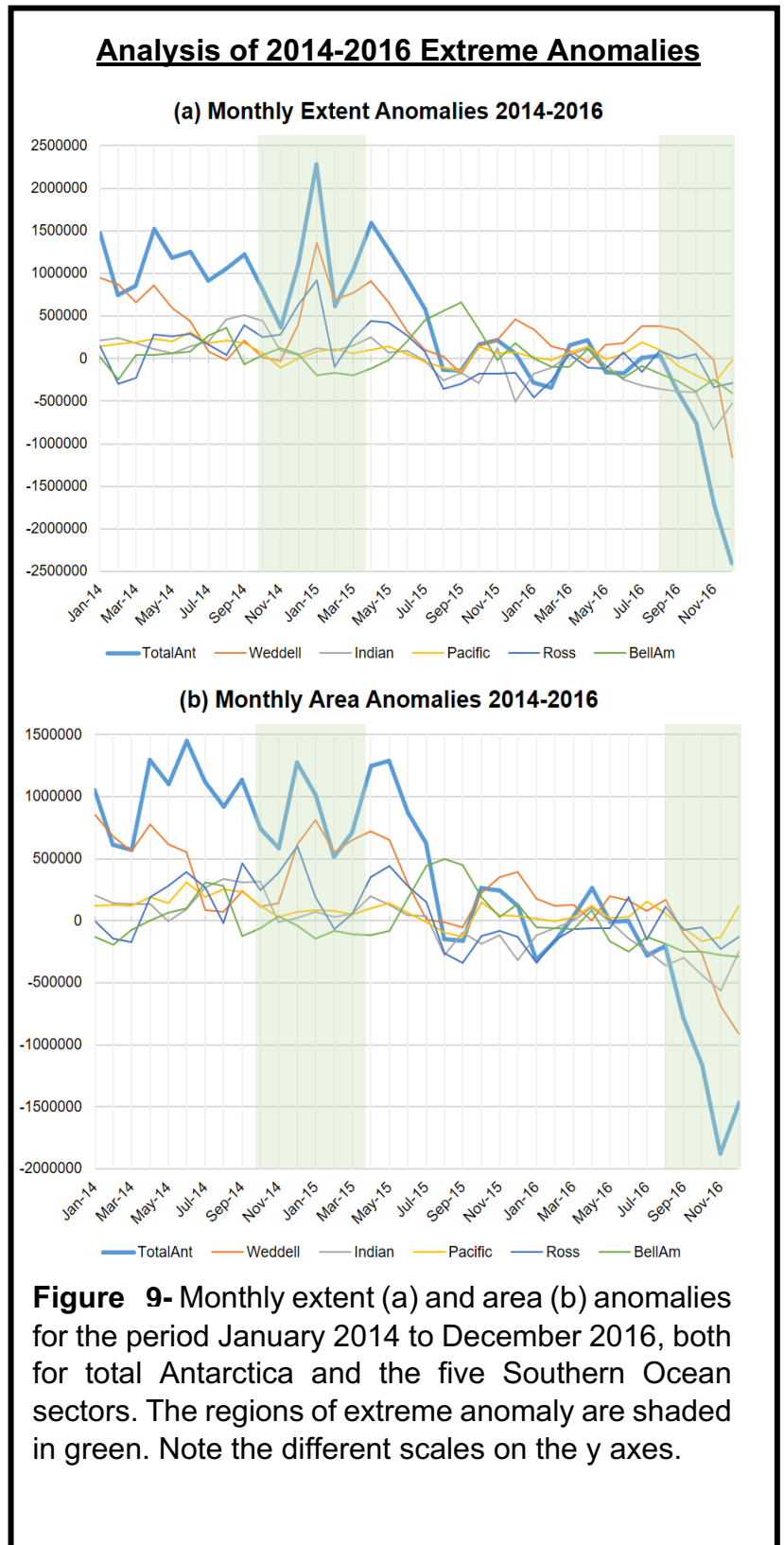


### 3.1.4. 2014/5 Extreme Positive Anomaly

As identified in figure 9 , in January 2015 there is a significant discrepancy between the area and extent anomalies, with the extent anomaly  $\sim 120,000\text{km}^2$  greater than the area anomaly. When looking closer at this period, as in figure 9, it is clear that for the total Antarctica the two measures closely track each other in the months either side of January. Of particular interest are the regional results, which indicate that this trend is driven almost entirely by the Ross and Weddell Sea Sectors (extent anomaly exceeding area by  $\sim 70,000\text{km}^2$  and  $\sim 60,000\text{km}^2$ , respectively).

### 3.1.5. 2016 Extreme Negative Anomaly

Furthermore, at the very end of 2016 there is an extreme negative anomaly for both area and extent, with a steep decline in extent from August to December and area from August to November. The area anomaly decreases in December, however, leading to the extent anomaly being  $\sim 100,000\text{km}^2$  greater in magnitude than area. Figures ... indicate that declines in total Antarctic sea ice extent and area were largely driven by the pattern in the Weddell Sea sector. The decrease in area anomaly between November to December appear to be driven by the Ross, Pacific and Indian sectors.



## 3.2. Case Comparison Study: Weddell Sea

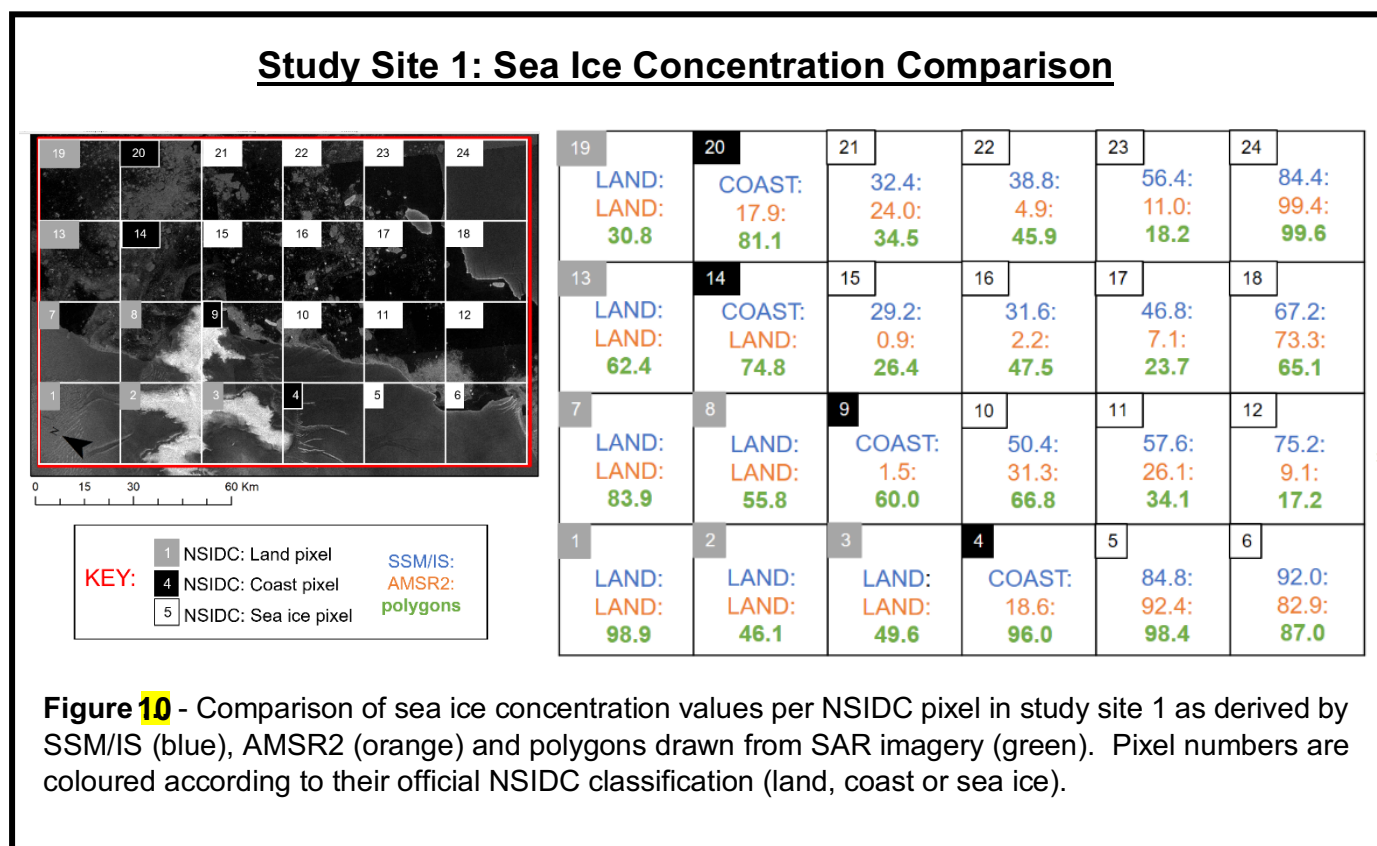
### 3.2.1. Study Site 1:

#### 3.2.1.1. Sea Ice Concentration:

Figure 10 shows the sea ice concentration values per NSIDC pixel as calculated by SSM/IS, AMSR2 and manual interpretation of SAR/MODIS for the 8 January 2019. Pixels 1-4, 7-9, 13-14 and 19-20 have all been classified as “land” or “coast” in the NSIDC dataset (and most for AMSR2 as well). However, interpretation of the SAR/MODIS imagery indicates that all of these pixels are covered in at least 30% ice. *NOTE: It appears that neither the SSM/IS nor AMSR2 datasets discriminate between ice shelves/icebergs and sea ice, as seen by the high concentration values in pixels 5 and 6 (mainly ice shelves) and 18 and 24 (mainly iceberg A68), and so this is used for the justification of all ice-covered areas outside the MODIS land boundary being included in the manual interpretation.*

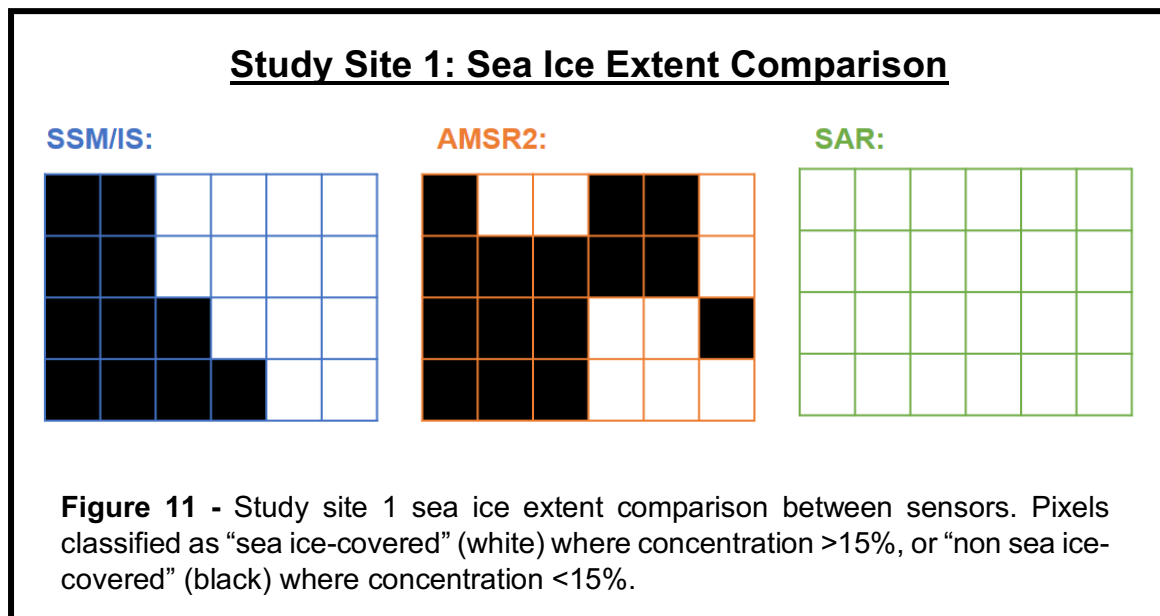
For all of the pixels that were classified by SSM/IS as “sea-ice covered”, there are considerable differences between concentration values recorded by the different sensors. Pixels 5, 6, 18 and 24 have the most consistent concentration values between sensors (within 15% of each other). The remaining pixels (10-12, 15-17 and 21-23) have a high degree of variation of concentration values between sensors (up to 66%). AMSR2 values are the lowest in each case.

The implications of these discrepancies in concentration values on measurements of *area* and *extent* are shown in figures 11 and 12.



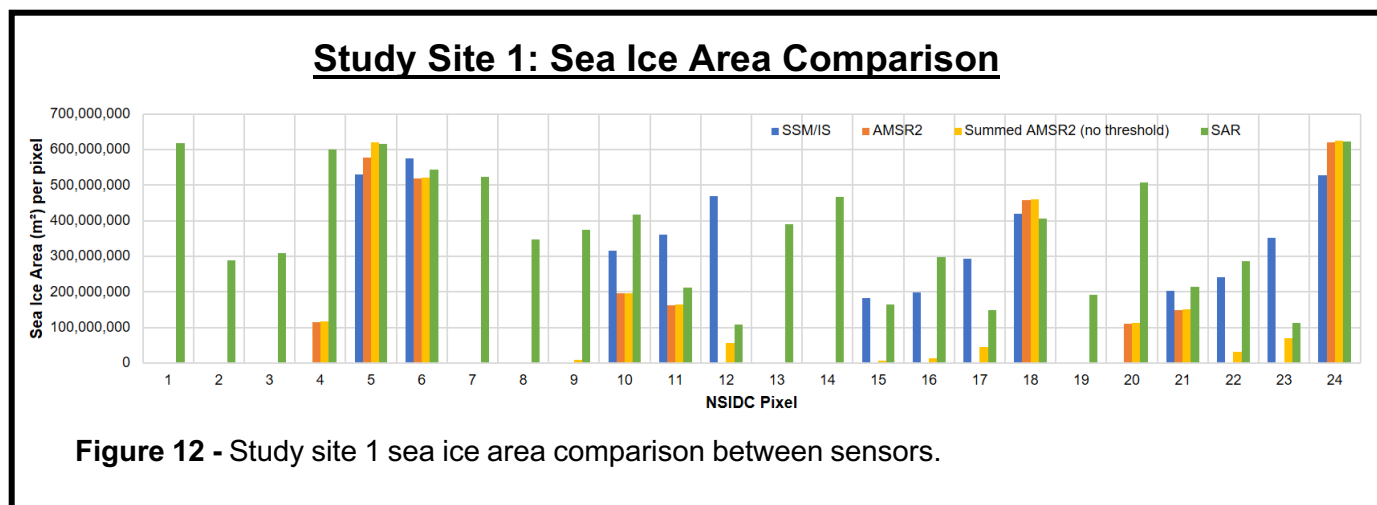
### 3.2.1.2. Sea Ice Extent:

Since sea ice extent is a binary measure (either 100% cover or 0% cover), its classification is defined by whether or not the measured concentration value exceeds the 15% threshold. As shown in figure 11 SMMR-SSM/I(S) defines 13/24 pixels (8,125 km<sup>2</sup>) in study site 1 as “sea-ice covered”; AMSR2 defines 9/24 pixels (5,625 km<sup>2</sup>) and SAR 24/24 pixels (15,000km<sup>2</sup>).



### 3.2.1.3. Sea Ice Area:

This translates to a total sea ice area of 4,668km<sup>2</sup> as measured by SSM/IS; 2,912km<sup>2</sup> by AMSR2 and 8,774km<sup>2</sup> by SAR. When the AMSR2 data is interpreted without the 15% threshold (i.e. including sea ice area where total pixel concentration < 15%), it gives a greater area of 3,199km<sup>2</sup>. The comparison of sea ice area values per pixel are shown on the graph in figure 12.



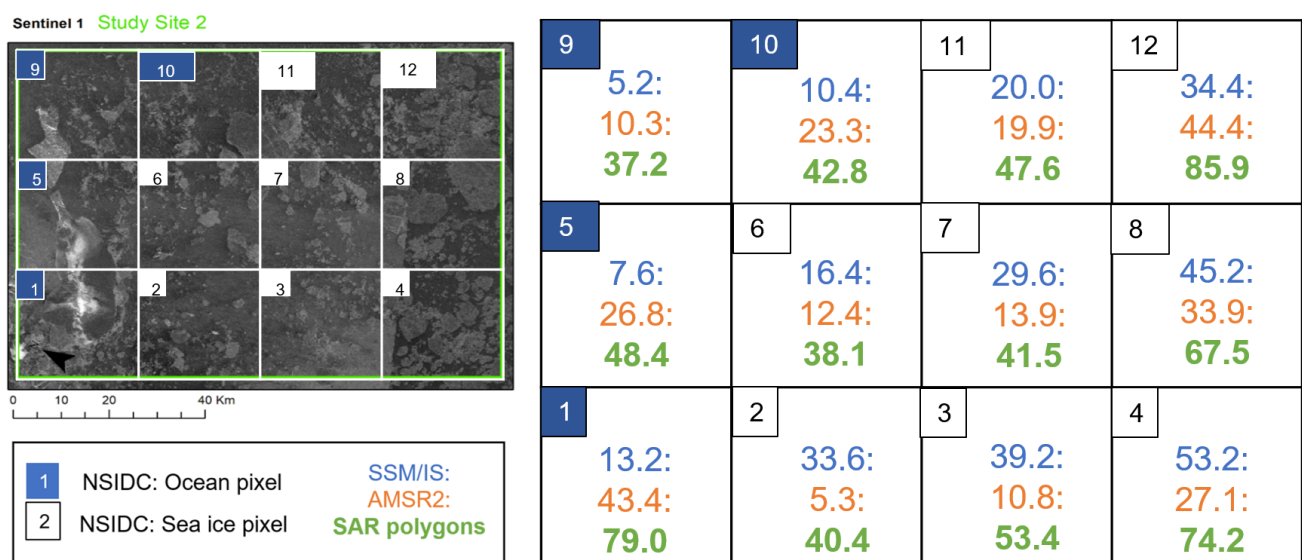
### 3.2.2. Study Site 2:

The comparison of SSM/I, AMSR2 and SAR-derived ice concentration, products for study site 2 are shown in figures 13-15.

#### 3.2.2.1. Sea Ice Concentration:

As this site is located away from land in the MIZ, there is no land mask applied for any dataset and every pixel has a value for sea ice concentration. However, similarly to study site 1, there are differences between these between the three sensors. The manual interpretation of SAR produced the highest concentration value in every pixel, all of which are significantly above the 15% threshold. In the SSM/IS data, pixels 1, 5, 9 and 10 have been measured to have sea ice concentrations <15% and so they have been classified as “ocean”. For AMSR2, pixels 2, 3, 6, 7 and 9 have concentrations below 15%.

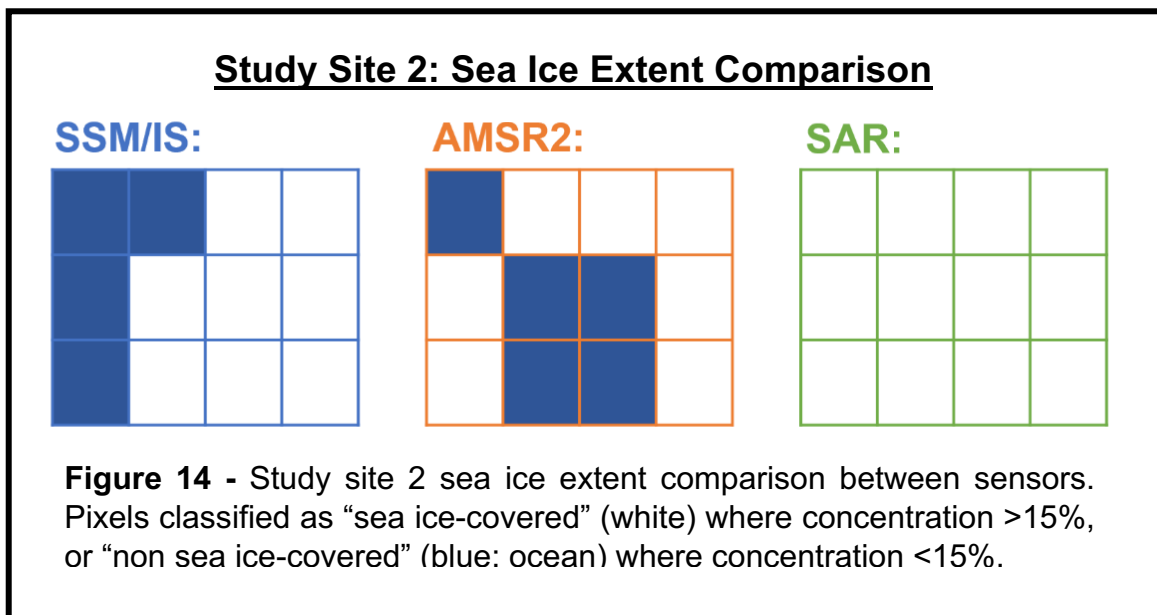
### Study Site 2: Sea Ice Concentration Comparison



**Figure 13** - Comparison of sea ice concentration values per NSIDC pixel in study site 2 as derived by SSM/IS (blue), AMSR2 (orange) and polygons drawn from SAR imagery (green). Pixel numbers are coloured according to their official NSIDC classification (ocean or sea ice).

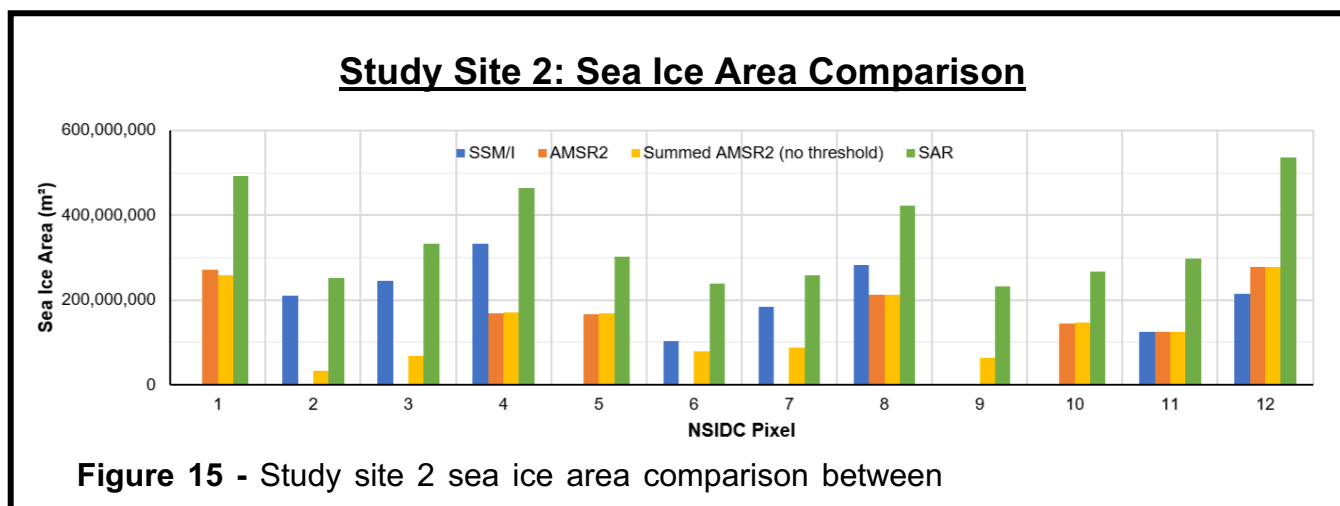
### 3.2.2.2. Sea Ice Extent:

The implications on the classification of sea ice *extent* are shown in figure 14. SSM/IS defines 8/12 pixels (5000km<sup>2</sup>) in study site 2 as sea ice covered; AMSR2 defines 7/24 pixels (4375km<sup>2</sup>) and SAR 12/12 pixels (7500km<sup>2</sup>).



### 3.2.2.3. Sea Ice Area:

This translates to a total sea ice *area* of 1,697km<sup>2</sup> as measured by SSM/IS; 1,367km<sup>2</sup> by AMSR2 and 4,100km<sup>2</sup> by SAR. When the AMSR2 data is interpreted without the 15% threshold it gives an area of 1691km<sup>2</sup>; 324km<sup>2</sup> greater than when all pixels with concentrations <15% are excluded. The comparison of sea ice area values per pixel are shown on the graph in figure 15.





## 4. Discussion

### 4.1. NSIDC Antarctic Sea Ice Trends

The NSIDC trends described in section 3.1 show an increase in Antarctic sea ice cover from 1978-2016, consistent with the widely reported increase in sea ice *extent* over this time that has gained attention in numerous published academic works and the media (e.g. Comiso et al., 2017; NZ Herald, 2016) due to its arguably counterintuitive nature in the context of the current warming global climate and drastic decline of Arctic sea ice. The findings of this research call into question how significant this reported trend really is.

#### 4.1.1. Relevance for Antarctic Sea Ice Mass Balance

When interpreting the NSIDC trends it is important to consider what the measures of *extent* and *area* are actually telling us about the state of Antarctic sea ice mass balance. As described in section 1.3 *extent* tells us how much of the Southern Ocean is covered in at least 15% sea ice cover, whereas *area* gives the actual area of ice-covered ocean, as calculated by extent x concentration (Parkinson et al., 1999). Sea ice *volume* is the ultimate variable required to assess changes in global sea ice mass balance, and this is calculated using *area* and *thickness*; therefore *area* is more useful as a measure than *extent*. Having said that, while both extent and area trends provide a two-dimensional description of sea ice cover since 1978, ultimately without an integration of the *thickness* distribution, their significance for understanding changes in sea ice mass balance over time is much diminished (Haas, 2003).

#### 4.1.2. Relationship between Extent and Area Trends

The results in section 3.1 describe the relationship between sea ice area and extent trends within the NSIDC time series. Understanding the patterns and causes of discrepancies identified in the datasets between the measures will be the focus of this analysis. A few previous studies have looked into the relationship between NSIDC sea ice extent and area measurements, but not in a huge level of detail. For example, a comparison of the Antarctic sea ice *extent* and *area* time series by Parkinson & Cavalieri (2012) indicated that in all cases the trends had the same sign but that the magnitudes of the two trends differ, with extents always larger than area.

##### **4.1.2.1. Relationship of Area and Extent Trends (Total Antarctica, 1978-2016):**

The findings of the NSIDC trend analysis in this study are consistent with these published findings, with sea ice extent and area anomalies in general shown to match very closely throughout the satellite record, and with the extent variable experiencing a slightly greater annual rate of change than area. However, as identified in the results of section 3.1.1 (figure 6), there are a number of extreme months throughout the time series with a significant discrepancy between the extent and area anomaly, predominantly with the magnitude of the

extent anomaly greatly exceeding that of area. This could be interpreted to suggest that the NSIDC reporting of sea ice maxima and minima using *extent* could be exaggerating the change in sea ice in extreme months. Interesting to note is that the majority of these extreme months experiencing discrepancies between area and extent anomalies occur during the austral summer season (November – February).

#### **4.1.2.2. Regional Patterns (5 Southern Ocean sectors, 1978-2016):**

Whilst there is little difference between the extent and anomaly trends 1978-2016 for total Antarctica, figure 7 shows how this average comprises five distinct regional trends, with three Southern Ocean sectors (Weddell, Indian and Ross) having an extent anomaly trend greater than area, and two sectors (Pacific and Bellingshausen-Amundsen) with the reverse pattern. These trends are particularly interesting as they call into question the significance of the overall trend reported by the NSIDC; are these distinct regional signals being dampened and overlooked by the nature of averaging trends over the entire vast continent?

#### **4.1.2.3. Discrepancies in Extreme Months:**

In order to understand the discrepancies seen between extent and area anomalies in extreme months it proves useful to analyse in detail the January 2015 extreme positive and December 2016 extreme anomalies.

As shown in figure 9 , the magnitude of the extent anomaly in January 2015 is  $\sim 120,000\text{km}^2$  greater than the area anomaly. Whilst considering that extent and area are both derived from the same measure of sea ice concentration, this is telling us that in this month the passive microwave sensors detected a significantly greater area of ocean than usual covered in a sea ice concentration  $>15\%$ , so that more pixels met the classification as “sea ice” in the NSIDC extent calculations. It is possible that the area anomaly, however, was not as extreme because the sea ice concentration values (in pixels  $>15\%$ ) did not increase as much. In reality this could reflect a situation where the sea ice has spread out more, covering a wider area than usual but at a reduced overall concentration.

The total opposite of this is relevant for the extreme negative anomaly in December 2016, where the extent anomaly is  $\sim 100,000\text{km}^2$  smaller than the area anomaly. Again, considering the relationship to sea ice concentration, this tells us that the sensors detected a smaller amount of ocean than usual exceeding the 15% concentration threshold (so fewer pixels classified as “sea ice”), but that the concentrations in pixels above this did not decrease as much. In reality this could reflect a situation where sea ice is more compact, covering a smaller area but at a higher overall concentration than usual.

#### **4.1.3. Potential Causes of Area and Extent Discrepancies in Extreme Months**

It is suggested here that the discrepancies in area and extent in these extreme months could be explained by physical processes, either continent-wide or regionally specific, or instrumental error.

#### 4.1.3.1. Physical Processes:

A physical process that could be responsible for these patterns is the strength and source of winds that can influence the divergence of sea ice (Comiso & Nishio, 2008). Where strong winds originate from the continental interior they can force the sea ice to diverge and hence reduce in concentration, and conversely, strong onshore winds can force the sea ice towards the coastline and become more compact (increased concentration). An interesting finding was made in the Bellingshausen Sea in October 2001, which was a period of anomalously low regional ice extent. Divers measured sea ice thickness of 20m and deduced that this had been caused by the presence of strong and persistent north-westerly winds that had forced and compacted the sea ice against the Antarctic Peninsula (Massom, 2006). In terms of extent and area, this would have been observed as a lower than average extent, but area measurements may not have been greatly affected due to the increased ice concentrations. However, since the ice thickness was so much greater than average, it suggests that the actual volume (and hence mass balance) of the sea ice in that region may not have been affected. This highlights the fact that without the incorporation of sea ice thickness measurements, our understanding of Antarctic sea ice mass balance is highly incomplete.

*Regional Drivers* - A closer analysis of the January 2015 and December 2016 anomalies suggests that there are regional drivers in the discrepancies between extent and area trends. Figure 9 show the pattern in each of the five Southern Ocean sectors for the January 2015 anomaly; it is clear that the ~120,000km<sup>2</sup> discrepancy between the extent and area anomalies is driven almost entirely by the conditions in the Weddell and Ross Sea sectors. The extent anomaly exceeds the area anomaly by a similar magnitude in both sectors, by ~60,000km<sup>2</sup> in Weddell and ~70,000km<sup>2</sup> in Ross. For the December 2016 minimum, the discrepancy was also mostly driven by the Weddell Sea sector, but with the influence of the Ross Sea much diminished. It is beyond the scope of this study to investigate the reasons behind these sectors as the main drivers of the discrepancy between extent and area, but I would suggest this as an interesting area for future research.

Having said this, some factors have been identified to explain why sea ice patterns in general vary between the five Southern Ocean sectors. For example, it has been suggested that strong decreases in sea ice extent in the Bellingshausen-Amundsen sector (in contrast to all other sectors) and noticeable increases in Ross sector are attributed to changes in atmospheric circulation (Parkinson & Cavalieri, 2012). Other factors, such as El Niño Southern Oscillation (ENSO), the Southern Annular Mode (SAM), the influence of high salinity shelf water (HSSW) and stratospheric ozone depletion, have also been proposed as influences on the regional heterogeneity (e.g. Armour et al., 2016; Holland and Kwok, 2012), but the relative influence of different factors is not well understood.

#### 4.1.3.2. Instrumental Error:

The fact that the majority of the discrepancies between extent and area anomaly values occur in extreme months during the austral summer (figures 6 and 8) could support the argument that the discrepancy results from instrument error. The NSIDC justify their use of sea ice *extent* (rather than area) when reporting trends to the public because they are cautious of the summertime ice concentration values recorded by the passive microwave sensors (NSIDC, 2008). These are the months in which there is likely to be a greater area of partial sea ice cover, which, as will be shown in the case study analysis in section 4.2, is the setting most susceptible to errors in the passive microwave signal (e.g. Parkinson et al.,

1999), and hence this may contribute to errors in the trend data. Previous studies have found that misinterpretation by the sensors of surface melt as open ocean renders them prone to underestimating ice concentration in summer months (e.g. Comiso & Kwok, 1996; Steffen & Schweiger, 1991; Fetterer & Untersteiner, 1998). However, the majority of these studies were based in the Arctic and the colder, drier and windier atmosphere in the Antarctic in comparison means that it is much less affected by surface melt and experiences smaller concentrations of soot (and other impurities) that influence the albedo and emissivity (Eicken, 2003). Therefore, this justification may not be as relevant in the Antarctic setting and area measurements should perhaps not be so readily dismissed.

#### **4.1.4. Implications of Findings**

This section has demonstrated that there are numerous uncertainties within these NSIDC reported sea ice trends, and in line with arguments by several authors (e.g. Lubin & Massom, 2006) this suggests that careful consideration must be exercised when drawing interpretations and conclusions from this data, especially when relating sea ice trends to climatic change.

In particular, both the explanation of the potential control of physical processes and of instrumental error on the discrepancy between extent and area in extreme months emphasize the significance of the 15% sea ice concentration threshold. I believe it raises concerns over the suitability of the 15% value as the threshold, and this will be discussed further in section 4.2.2.5 in relation to the Weddell Sea case study.

### **4.2. Case Comparison Study: Weddell Sea**

The results of the Weddell Sea case comparison study, as described in section 3.2, highlight the considerable uncertainties in the measurement of Antarctic sea ice concentration from satellite-borne passive microwave sensors. This is of significance because this is the raw data that feed into the NSIDC sea ice extent and area trends, as discussed in section 4.1. The case study also gives an insight into the difficulties involved in validating passive microwave data.

#### **4.2.1. Difference in Measurements between Sensors**

For both study sites there were significant differences in ice concentration values identified between sensors (figures 10-15). This translates into contrasting patterns of sea ice extent, largely relating to the designation of the 15% threshold. Total sea ice area values were also consistently underestimated by the passive microwave sensors, with both SSM/I and AMSR2-derived areas for both study sites not even reaching half of the area derived from the higher resolution SAR data. The potential causes of these discrepancies, and implications for the sea ice area and extent trends, will be outlined in the following section.

## **4.2.2. Potential Causes of Discrepancies between Sensors**

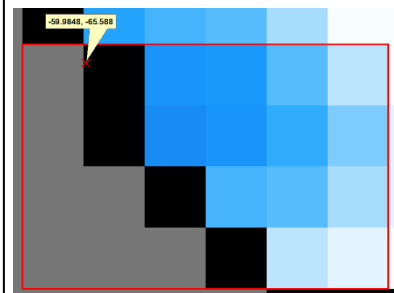
### **4.2.2.1. NSIDC Land Mask:**

The most obvious cause of the observed differences between ice concentration measurements found in this research (particularly for study site 1) is the definition of some pixels as “land” and “coast” in the passive microwave concentration datasets that from the higher resolution SAR and MODIS imagery are clearly ice/ocean. Furthermore, no distinction appears to be made between sea ice and terrestrial-borne ice (ice shelves and icebergs). Both of these factors are problematic for the accurate assessment of sea ice extent, area and mass balance. Figure 16 is a photograph taken on 25 January 2019 (17 days after the SAR imagery for this study) at a location well within the area classified



**Figure 16 -**

Photograph taken on 25/01/2019 at the location within study site 1 shown on the inset map: 65.588°S, 59.9848°W.



as “land” by the NSIDC and AMSR2, but that is clearly a region of ocean and sea ice. The sea ice in this area is therefore not accounted for in the measurements.

The NSIDC land/coast mask would have been defined in 1978 at the beginning of the satellite observations. However, the coastline of Antarctica is extremely dynamic, with episodic calving events (such as that of iceberg A-68 in July 2017 (visible in the study area); Rignot et al., 2017) able to change the position of the coastline by 1000s of kilometres in a very short period of time, opening up previously unexposed ocean to the formation of sea ice. Despite this there is a reluctance to update the masks as it would likely be problematic for the continuity of the sea ice extent and area time-series. Conversely, the argument could also be made that the errors introduced by this issue may well be averaged out over the whole continental margin.

### **4.2.2.2. Spatial Resolution of Passive Microwave Data:**

The poor spatial resolution is likely to represent the main source of inaccuracy in the passive microwave data. This is because the large fields of view inhibit the sensors’ ability to resolve smaller morphological features such as leads and melt structures (Lubin & Massom, 2006). In theory the relatively higher spatial resolution of the AMSR2 sensor should therefore provide better accuracy than the SSM/I data (6.25km vs. 25km). However, the findings in the two Weddell Sea study sites show that, if anything, the SSM/I ice concentrations correlate more closely with the manual interpretations from SAR than those of AMSR-2 (see figures 10-15). It appears that the AMSR2 data consistently underestimates the sea ice concentration.



#### **4.2.2.3. Mixed-Pixel Problem:**

The pixels in both study areas with the largest discrepancies in concentration values between sensors are all located in areas of partial and more dispersed ice coverage; characteristic of the MIZ. This is in line with a number of previous studies that have identified the MIZ as an environment with the greatest retrieval errors in sea ice concentration from passive microwave sensors, largely caused by the overlapping microwave emissivities of wet/thin sea ice and the open ocean (especially in summer months, as in this study) (e.g. Bruckner et al., 2014; Comiso et al., 2011). Spectral signatures of different ice and surface types become averaged within a pixel and are difficult to unmix (Lubin & Massom, 2006). This presents a challenge to the definition of the sea ice edge, as discussed in section 4.2.2.4.

#### **4.2.2.4. Definition of the Ice Edge:**

The ice edge is currently defined by the 15% sea ice concentration threshold that marks the difference between “sea ice-covered” and “not sea ice-covered” pixels in the NSIDC sea ice extent dataset. However, in reality the composition of the ice edge can vary spatially and temporally. Firstly, throughout the seasonal cycle it is subject to the development of grease ice through nilas, pancake ice and young ice, to first year (and in some locations, multiyear) ice, all of which have contrasting physical and radiative characteristics that complicate the detection of surface emissivity signals by the passive microwave sensors (NSIDC, 2016). Massom et al. (1992) found that for this reason passive microwave sensors typically underestimate sea ice concentrations in these regions. Moreover, wind patterns can determine whether the ice edge is compact (onshore winds) or diffuse (off-shore winds) or somewhere in between. When diffuse, ice edges can extend meridionally for tens of kilometres (Lubin & Massom, 2006). This is where the designation of the 15% ice concentration threshold becomes important, because if concentrations fall below 15% in this more diffuse zone, the satellite-derived ice edge could be substantially further poleward than the actual ice edge (and hence extent reduced). On the other hand, if concentrations were to keep above the 15% threshold (even if just very marginally), the ice edge could be located much further from the coast and the measurement of sea ice extent significantly greater.

This suggests that the variation in measurements between sensors, rather than the physical conditions themselves, could be the difference between a pixel being defined as “sea ice-covered” or not. This effect can be seen particularly clearly in the study site 2 results (figure ...), where the designation of pixels as “sea ice-covered” or not by the three different sensors using the 15% threshold for was completely different. For some pixels, the difference between sensors was large, however others the margins were not very significant (e.g. pixel 6 recorded concentrations of 16.4% from SSM/I but 12.4% from AMSR2; thus classified as “sea ice-covered” in the former but not the latter).

The accuracy and consistency of detection of this ice edge location is therefore an important factor affecting the reliability of the satellite-derived Antarctic sea ice time series (Lubin & Massom, 2006). Relating back to the discussion the NSIDC trends in section 4.1, this could offer a potential explanation of the large extent and area discrepancies observed in some extreme months.

#### **4.2.2.5. Suitability of the 15% Threshold:**

The above discussion raises questions over the suitability of this threshold. Although 15% has typically been the value used for the definition of the ice edge, this is somewhat arbitrary and has not been subject to a full validation (Lubin & Massom, 2006). Parkinson et al. (1999) conducted a review of its suitability for extent trends by re-calculating the Arctic trends using thresholds of 20% and 30%, finding that although the resultant values were different, the trends were very similar (all within one standard deviation of the 15% trend). This seems to justify the use of 15% but it remains uncertain how universally applicable these findings are to the Antarctic setting and 20 years on (Lubin & Massom, 2006). Furthermore, there may be a seasonal signal to the accuracy. A validation of the SSM/I-derived Antarctic ice edge position conducted by Worby & Comiso (2004) using a combination of limited ship observations and Radarsat SAR found that the use of the 15% threshold is generally accurate between March and October (autumn-spring), but that in November to December it results in the SSM/I-derived ice edge located on average 1.00-1.96° further south than observations indicate. The findings of the Weddell Sea case study agree with this, having found the passive microwave sensors (particularly AMSR2) to regularly underestimate sea ice cover. When the sea ice area was calculated using AMSR2 but without the 15% threshold, it produced a higher value closer to that of the manual interpretation.

#### **4.2.3. Implications of Case Study Findings**

It must be emphasised that the findings of this case study are very much an isolated setting are likely by no means representative of the whole continent, however they do flag up these potentially problematic and widespread issues that seemingly have thus far been neglected/ignored. I would suggest a systematic evaluation of these identified sources of error across the continent deserves further study, if we are to improve our understanding of the significance of reported changes in Antarctic sea ice variability.

## **5. Conclusions**

### **5.1. Summary of Key Findings:**

In this report an assessment of the relationship between sea ice area and extent measurements in the Southern Ocean has been conducted, both through the analysis of NSIDC trends since 1978 and the and those derived from the passive microwave sea ice concentration products in a case study in the Weddell Sea. The significance of the reported rise in Antarctic sea extent over the past 40 years has been brought into question, considering the large degree of spatial and seasonal variability observed in this study to be concealed within this average (and rather small in magnitude) trend. Although congruent sea ice extent and area trends were found throughout the NSIDC dataset, divergences in some extreme monthly anomalies were found, mostly with the extent anomaly much greater than that of area. It was discussed that this could be a reflection of either physical processes (e.g. wind behaviour) that may vary between regions, or instrumental errors. The Weddell Sea case study gave further insight into these uncertainties in the passive microwave datasets, identifying issues relating to the NSIDC land mask, low spatial resolution, definition of the ice edge and the suitability of the 15% ice concentration threshold.

## 5.2. Implications:

The evidence presented here could be suggesting that *area* may be the better measure of sea ice in months of extreme anomaly, but mainly demonstrates that we ought to be very cautious when interpreting trends based on just one of these measures. Furthermore, the fact that sea ice thickness has been shown to vary significantly year on year (e.g. Massom, 2006) proves that our understanding of sea ice mass balance cannot rely purely on the record of spatial coverage. It points to the conclusion that the reported rising trend in Antarctic sea ice cover in the past few decades does not actually tell us much about the changes that have occurred in the amount of sea ice present around the continent. Ultimately, therefore, the question of whether *extent* or *area* is the better measure to assess trends through time is rendered insignificant when considering the fact that the vital parameter of ice thickness is missing.

However, despite all of the uncertainties highlighted in this study surrounding the passive microwave-derived NSIDC record of Antarctic sea ice trends, it must be acknowledged that it is still the longest and most reliable climate dataset in existence on Earth (Parkinson & Cavalieri, 2012), and that the value of such a resource must not be underestimated.

## 5.3. Suggestions for Future Research:

Throughout the completion of this study, a much more complex picture surrounding the assessment of Antarctic sea ice patterns was found than initially expected. Several issues were identified that would have been beyond the scope of the report to investigate further. As a result, selection of suggestions for future research have been proposed:

- ⇒ **Integration of Thickness Data** - An integration of thickness into the monitoring of sea ice trends will be imperative if we are to more accurately inform oceanographic and atmospheric studies and hence our understanding of the present and future climate system. It could be interesting to assess any scope for CryoSat2 and ICESat altimetry data to be integrated with the passive microwave datasets, and whether this would provide any further insight into the drivers of discrepancies between area and extent trends found in this study.
- ⇒ **Integration of higher resolution data into trend datasets** – Now that we have a range of higher resolution datasets able to more accurately monitor global sea ice cover than the 25km SSM/I(S) suite, attempts ought to be made to incorporate these into the continued measurement of change through time. Having an accurate record of changes in sea ice cover is especially critical now due to the large uncertainty surrounding the future climate of the Southern Ocean and globally.
- ⇒ **Regional and Seasonal Patterns** – Further investigations into the magnitude and drivers of discrepancies between ice area and extent measurements in different regions and throughout the annual cycle would be recommended.
- ⇒ **Review of Land Masks** - I would suggest that a systematic review of the NSIDC land mask would be desirable. In particular, a review ought to be incorporated in any assessment of a future transition away from the traditional US SSM/I(S) to higher resolution sensors in the reporting of sea ice trends.

⇒ **Review of 15% Threshold** – In light of the findings of this study I would suggest there is a strong need to review the suitability of the 15% threshold for determining sea ice extent in the present day Antarctic setting

## 6. Reference List

Armour, K. C., Marshall, J., Scott, J. R., Donohoe, A. and Newsom, E. R. (2016) Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nature Geoscience*. 9, pp. 549-554.

Arrigo, K. R. and Thomas, D. N. (2003) Large scale importance of sea ice biology in the Southern Ocean. *Antarctic Science*. 16 (4), pp. 471-486.

Brucker, L., Dinnat, E. P., Picard, G. and Champollion, N. (2014) Effect of snow surface metamorphism on Aquarius L-band radiometer observations at Dome C, Antarctica. *IEEE Transactions on Geoscience and Remote Sensing*. 52 (11), pp. 7408-7417.

Cavalieri, D. J. and Parkinson, C. L. (2008) Antarctic sea ice variability and trends, 1979-2006. *Geophysical Research Letters*, 6.

Cavalieri, D. J. (1994) A microwave technique for mapping thin ice. *Journal of Geophysical Research*. 99, pp. 12,561-12,572.

Cavalieri, D. J., Crawford, J. P., Drinkwater, M. R., Eppler, D. T., Farmer, L. D., Jentz, R. R. and Wackerman, C. C. (1991) Aircraft Active and Passive Microwave Validation of Sea Ice Concentration From the Defense Meteorological Satellite Program Special Sensor Microwave Imager. *Journal of Geophysical Research*. 96 (C12), pp. 21989-22008.

Colton, M., and G. Poe (1999) Intersensor calibration of DMSP SSM/Is: F-8 to F-14; 1987-97. *IEEE Trans. Geoscience Remote Sensing*. 37, pp. 418–439.

Colwell, S. and Turner, J. (2003) The relationship between Antarctic coastal temperatures and sea ice extent. In: *Preprints of the Joint Antarctic Automatic Weather Station Annual Meeting, Antarctic Meteorological Research Center Annual Meeting, and Antarctic Mesoscale Prediction System (AMPS) Users' Workshop, Madison, WI, June 13-26*.

Comiso, J. C. & Kwok, R. (1996) Surface and radiative characteristics of the summer Arctic sea ice cover from multisensor satellite observations. *Journal of Geophysical Research: Atmospheres*. 101 (C12), pp. 28397-28416.

Comiso, J. C., Gersten, R. A., Stock, L. V., Turner, J., Perez, G. J. and Cho, K. (2017) Positive Trend in the Antarctic Sea Ice Cover and Associated Changes in Surface Temperature. *Journal of Climate*. 30, pp. 2251-2267.

Comiso, J. C., Kwok, R., Martin, S. and Gordon, A. L. (2011) Variability and trends in sea ice extent and ice production in the Ross Sea. *Journal of Geophysical Research: Oceans*. 116 (C4).

- Comiso, J. C., and Nishio, F. (2008) Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data. *Journal of Geophysical Research: Oceans*. 113(C2)
- Eicken, H. (2003) The role of Arctic sea ice in transporting and cycling terrestrial organic matter. Pp. 45-53 in: Stein, R. and MacDonald, R. W. (eds.) *The Organic Carbon Cycle in the Arctic Ocean*. Springer-Verlag, Berlin.
- Fetterer, F. and Untersteiner, N. (1998) Observations of melt ponds on Arctic sea ice. *Journal of Geophysical Research*. 103 (C11), pp. 24,821-24,835.
- Fetterer, F., Knowles, K., Meier, W. and Savoie, M. (2016) updated daily. Sea Ice Index, Version 2. National Snow and Ice Data Center.
- Forster, R. R., Long, D. G., Jezek, K. C., Drobot, S. D. and Anderson, M. R. (2001) The onset of Arctic sea-ice snowmelt as detected with passive- and active-microwave remote sensing. *Annals of Glaciology*. 33, pp. 85-93.
- Haas, C. (2003) Dynamics versus thermodynamics: The sea-ice thickness distribution. Pp. 82-111 in Thomas, D. N. and Dieckmann, G. S. (eds.) *Sea Ice: An Introduction to its Physics, Biology, Chemistry and Geology*. Blackwell Scientific, Oxford, UK.
- Holland, P. R. and Kwok, R. (2012) Wind-driven trends in Antarctic sea-ice drift. *Nature Geoscience*. 5 (12), pp. 872-875.
- Liu, Y., Key, J. and Mahoney, R. (2016) Sea and freshwater ice concentrations from VIIRS on Suomi NPP and Future JPSS Satellites. *Remote Sensing*. 8 (523), pp. 1-20.
- Lubin, D. and Massom, R. (2006) *Polar Remote Sensing (Vol. 1: Atmosphere and Ocean)*. Springer-Verlag, Chichester.
- Macalady, A. and Thomas, K. (2017) *Antarctic Sea Ice Variability in the Southern Ocean-Climate System: Proceedings of a Workshop*. The National Academies Press, Washington, DC.
- Massom, R. A., Comiso, J. C., Worby, A. O., Lytle, V. I. and Stock, L. (1999) Regional classes of sea ice cover in the East Antarctic pack from satellite and *in situ* data during the winter time period. *Remote Sensing of the Environment*. 68 (C1), pp. 68-76.
- Massom, R. A., Stammerjohn, R. C., Smith, M. J., Pook, R. A., Iannuzzi, N., Adams, D. G., Martinson, M., Vernet, W. R., Fraser, L. B., Quetin, R. M., Ross, Y., Massom, and H. R. Krouse. (2006) Extreme anomalous atmospheric circulation in the West Antarctic Peninsula region in austral spring and summer 2001/2, and its profound impact on sea ice and biota. *Journal of Climate*. 19, pp. 3544-3571.
- Massonnet, F., Guemas, V., Fuckar, N. S. and Doblas-Reyes, F. J. (2015) The 2014 high record of Antarctic sea ice extent. *Bulletin of the American Meteorological Society*, 96 (12), pp. 163-167.
- Maykut, G. A. (1978) Energy exchange over young sea ice in the central Arctic. *Journal of Geophysical Research*. 83 (C7), pp. 3646-3658.



- Maykut, G. A. (1986) The surface heat and mass balance. Pp. 395-463 in Unterstriner, N. (ed.) *The Geophysics of Sea Ice* (Series B: Physics Vol. 196). Plenum Press, New York.
- Meier, W. N. (2005) Comparison of passive microwave ice concentration algorithm retrievals with AVHRR imagery in arctic peripheral seas. *IEEE Transactions on Geoscience and Remote Sensing*. 43 (6), pp. 1324-1337.
- Melling, H. (1998) Detection of features in first-year pack ice by synthetic aperture radar (SAR). *International Journal of Remote Sensing*. 19, pp. 1223-1249.
- NZ Herald (2016) "Why is Antarctic sea ice increasing?", *NZ Herald*, 6 July. [https://www.nzherald.co.nz/nz/news/article.cfm?c\\_id=1&objectid=11669794](https://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=11669794) [accessed 25/01/2019]
- Parkinson, C. L. and Cavalieri, D. J. (2012) Antarctic sea ice variability and trends, 1979-2010. *The Cryosphere*. 6, pp. 871-880.
- Parkinson, C. L., Rind, D., Healy, R. J. and Martinson, D. G. (2001) The impact of sea ice concentration accuracies on climate model simulations with the GISS GCM. *Journal of Climate*. 14, pp. 2606-2623.
- Parkinson, C. L., Cavalieri, D. J., Goersen, P., Zwally, H. J. and Comiso, J. C. (1999) Arctic sea ice extents, areas and trends, 1978-1996. *Journal of Geophysical Research*. 104 (C9), pp. 20837-20856.
- Raytheon, (2000) Special Sensor Microwave/Imager user's interpretation guide: Developed for DMSP Program Office. *USAF Space and Missile Systems Center*. 96.
- Rignot, E. J., Larour, E. Y., Scheuchl, B., Khazendar, A., Bamber, J. L. and Mouginot, J. (2017) What happened to Larsen C? *American Geophysical Union, Fall Meeting 2017*.
- Steffen, K., and Schweiger, A. (1991) NASA team algorithm for sea ice concentration retrieval from Defense Meteorological Satellite Program special sensor microwave imager: Comparison with Landsat satellite imagery. *J. Geophys. Res.* 96 (C12), pp. 21,971-21,987
- Timmermann, R., Beckmann, A. and Helmer, H. H. (2001) The role of sea ice in the freshwater budget of the Weddell Sea, Antarctica. *Annals of Glaciology*. 33, pp. 419-424.
- Turner, J., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J. and Phillips, T. (2015) Recent changes in Antarctic Sea Ice. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*. 373 (2045), pp. 140-163.
- Woodhouse, I. H. (2006) *Introduction to Microwave Remote Sensing*. CRC Press,
- Worby, A. P. and Comiso, J. C. (2004) Studies of the Antarctic sea ice edge and ice extent from satellite and ship observations. *Remote Sensing of Environment*. 92, pp. 98-111.